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Herbicidal strategies to control *Phalaris brachystachys* in a wheat-sunflower rotation: a simulation approach

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Abstract

Phalaris brachystachys is a common and troublesome weed in winter cereals in Mediterranean countries. A deterministic model was developed to simulate *P. brachystachys* seedbank dynamics in the wheat-sunflower rotation, a commonly practiced cropping system in southern Spain, under different herbicide-based management scenarios: no herbicide application, full herbicide dose (standard rate) and two reduced dose rates (75 and 50% of the standard rate). Without treatment, a steady increase of the seed bank is predicted up to an equilibrium level of 54,859 seeds m^{-2} (575 plants m^{-2}) after 25 years. Full dose herbicide applications in wheat years resulted in a progressive seed bank decline over years. Reducing the efficacy of the herbicide by using 50% or 75% of the recommended rate resulted in no long-term seed bank decline. Instead, a population increase until equilibrium densities is predicted. A sensitivity analysis showed that seedling survival and fecundity were the most sensitive demographic parameters under the full dose strategy, whereas fecundity and seedbank mortality were the most sensitive parameters under reduced dose strategies. Reduced dose strategies tended to be less sensitive than the full dose strategy. Simulations indicated that long-term control of this weed may be attained under full dose, highly effective, herbicide applications. Unless effectiveness could be maintained at very high levels, reduced herbicide doses may not be a recommendable option for the long-term control of this species in a wheat-sunflower rotation.

Additional key words: population model; seed bank; sensitivity analysis; short-spiked canarygrass; simulation; sunflower-wheat rotation.

Resumen

Estrategias para el control con herbicidas de *Phalaris brachystachys* en una rotación trigo-girasol: un modelo de simulación

Phalaris brachystachys es una de las malas hierbas más importantes en el cultivo de trigo en los países mediterráneos. Un modelo determinístico fue desarrollado para simular la dinámica del banco de semillas de *P. brachystachys* en una rotación trigo-girasol, un sistema de cultivo utilizado frecuentemente en el sur de España, bajo diferentes escenarios de manejo basado en el uso de herbicidas: sin herbicidas, dosis completa (recomendada por el fabricante), y dos dosis reducidas (75% y 50% de la dosis recomendada). Al usar el tratamiento sin herbicidas, el banco de semillas alcanza un nivel de equilibrio con 54.859 semillas m^{-2} (575 plantas m^{-2}) a los 25 años. La aplicación de la dosis completa en el año de trigo resultó en una reducción progresiva del banco de semillas. El uso de dosis reducidas no resultó en una disminución en el banco de semillas a largo plazo. El análisis de sensibilidad mostró que la supervivencia de plantas y la fecundidad son los parámetros demográficos más sensibles al aplicar la dosis completa del herbicida, mientras que la fecundidad y la mortalidad en el banco de semillas fueron los parámetros más sensibles al aplicar las dosis reducidas de herbicidas. De acuerdo con el análisis de sensibilidad, la estrategia de dosis reducidas tendió a ser menos sensible que la estrategia de dosis completa. Las simulaciones indicaron que el control a largo plazo de esta mala hierba solo puede alcanzarse con el uso de la dosis completa del herbicida. El uso de dosis reducidas de herbicidas que no alcancen una alta eficacia en el control no es una opción recomendable a largo plazo para el control de esta especie en la rotación trigo-girasol.

Palabras clave adicionales: alpiste; análisis de sensibilidad; banco de semillas; modelo poblacional; rotación trigo-girasol; simulación.

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Introduction

Phalaris brachystachys Link (short-spiked canary grass) is a winter annual grass considered to be among the most troublesome weeds of cereal crops in Mediterranean areas (Jimenez-Hidalgo *et al*., 1997). It is particularly abundant in southern Spain (Gonzalez-Andujar & Saavedra, 2003), where it represents a major problem in winter cereals. This weed is highly competitive and produces large numbers of seeds (Gonzalez-Andujar *et al*., 2005), and it can decrease wheat (*Triticum aestivum*) yield by 16% to 60% (Afentouli & Eleftherohorinos, 1999). In southern Spain cereal crops are frequently managed in rotation with sunflower (*Helianthus annuus*), a spring crop. In sunflower years, winter weeds are severely reduced by tillage operations conducted in mid to late winter and by seedbed preparation and sowing in late winter (Jimenez-Hidalgo, 1993). In addition, herbicide applications in the wheat year are commonly used to control *P. brachystachys* populations in this cropping system (Saavedra *et al*., 1989). Soil characteristics of the typical cereal areas in Southern Spain (deep, clayey soils) and the scarcity of water justify this rotation. Wheat-sunflower rotation improves the use of water and nutrients by the crop plants due to the different rooting system of both crop species, and also facilitates the management of weed infestations because of the alteration between a winter and a spring crop (Gonzalez-Andujar & Saavedra, 2003).

Although herbicides are widely used in the wheat year (*e.g.* clodinafop), the relatively high cost of these products and the social concern about their environmental impact, have led researchers and producers to re-evaluate conventional decision-making methods (Gonzalez-Diaz *et al*., 2009). Most studies have shown that herbicide rates below those recommended can provide sufficient weed control without affecting crop yield (Zhang *et al*., 2000; Fernandez-Quintanilla *et al*., 2006). In fact, short term studies conducted with *Phalaris* spp. in southern Spain have shown that reduced herbicide rates can provide sufficient control without reducing crop yield (Gaitan *et al*., 2007). However, long term studies on the population dynamics of *P. brachystachys* in the wheat-sunflower cropping system under low-dose herbicide applications have not been developed yet. Understanding the long-term dynamics of plant populations is fundamental to devising strategies for their management (Bullock *et al*., 2008). Population dynamic models are useful in simulating the long-term dynamics of weed populations (Holst *et al*., 2007). The objective of this study was to model the population dynamics of *P. brachystachys* in the wheat-sunflower rotation system in southern Spain and use the model to address the following specific questions: a) what is the long-term dynamics of *P. brachystachys* populations?, and b) what impact does a range of herbicide dose applications do on the seedbank size of *P. brachystachys*?

Material and methods

The model corresponds to the integration of two population dynamics sub-models of *P. brachystachys* under the wheat-sunflower rotation: the wheat sub-model and the sunflower sub-model.

Wheat sub-model

The wheat sub-model is based on a modification of a previously developed model for *P. brachystachys* in wheat (Gonzalez-Diaz *et al*., 2009) allowing for splitting the seed bank into two soil layers: the deep seed bank (> 5 cm) and the shallow seed bank (0-5 cm).

Seed bank density in the upper soil layer at time t is indicated as $BS_{sw,\,t}$. Each year, a fraction m of seeds experiences natural mortality and a fraction g germinates successfully. The density of plants that emerge and survive until the adult stage is indicated as P_t. A fraction s survives until reproduction. Each surviving plant will produce an average f viable seeds, representing the seed output that returns to the seed bank. A fraction p of the total seed rain is assumed to be lost before entering the seed bank due to biotic and abiotic factors. The dynamics is thus described by,

$$BS_{sw,\,t+1} = (1-g)\,(1-m)\,BS_{ss,\,t} + gsf\,(1-p)P_t \quad [1]$$

where BS_{ss} is the shallow seedbank carried over through the sunflower year, where no seed input to the soil is allowed.

The effect of weed plant density on fecundity (density-dependent factor) f is introduced by,

$$f = f_0/(1 + aP_t) \quad [2]$$

where f_0 is the number of seeds produced by an isolated plant without intraspecific competition, and a is the plant-free area required by a plant to produce f_0 seeds.

A fraction c of emerged seedlings is suppressed by herbicide application. Thus, the density of surviving seedlings is

$$P_t = (1 - c)g\, BS_{ss,\, t} \quad [3]$$

The seed bank density in the deep soil layer at time t is indicated as $BS_{dw,\, t}$

$$BS_{dw,\, t+1} = (1 - m)\, BS_{dw,\, t} \quad [4]$$

where $BS_{dw,\, t}$ is the deep seed bank in sunflower crop at time t. There are no *P. brachystachys* emergences from depths greater than 5 cm.

Sunflower sub model

In sunflower years, *P. brachystachys* does not produce seeds since all plants are removed at the vegetative stage by tillage operations in mid to late winter and seedbed preparation in late winter. Thus, the weed population survives sunflower years in the seed bank only. The seed bank is significantly affected by the vertical movement of seeds in the soil as a result of tillage operations (mouldboard plough followed by rotary harrow passes) (Fig. 1).

The shallow seed bank in sunflower years (BS_{ss}) is modelled as,

$$BS_{ss,\, t+1} = [BS_{sw,\, t}\, (1 - l_1)\, (1 - l_2) + BS_{dw,\, t}\, l_3]\, d_1 d_2 \quad [5]$$

where l_1, l_2 are the rates of seed movement from the shallow to the deep seed bank after mouldboard plough and harrow passes, respectively; I_3 is the rate of seed movement from the deep to the shallow seed bank after mouldboard plough; and d_1, d_2 are seed survival rates after mouldboard plough and harrow passes, respectively.

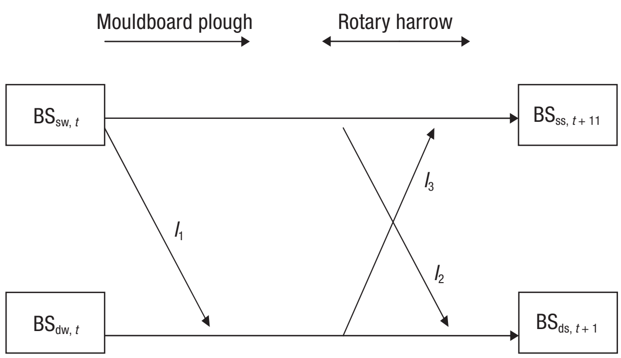

Figure 1. Movement of seeds in the soil in sunflower crop: l_1 rate of seeds transferred to the deep seed bank; l_2 rate of seeds transferred to the deep seed bank; l_3 rate of seeds transferred to the surface seed bank; $BS_{sw,\, t}$ superficial seed bank in wheat; $BS_{dw,\, t}$ deep seed bank in wheat; $BS_{ss,\, t+1}$ superficial seed bank in sunflower; $BS_{ds,\, t+1}$ deep seed bank in sunflower; the subscript "t" indicates the time.

The deep seed bank in sunflower crop (BS_{ds}) is given by

$$BS_{ds,\, t+1} = [BS_{dw,\, t}\, (1 - l_3) + BS_{sw,\, t}\, l_1 l_2]\, d_1 d_2 \quad [6]$$

The values of the different parameters of the model are presented in Table 1 and were taken from Jimenez-Hidalgo (1993), except the fecundity parameter *(fo)* obtained from Gonzalez-Diaz *et al*. (2009). For the simulation, the initial population size of the shallow seed bank of the weed after the sunflower year was set at 100 seeds m^{-2}. This density correlates with a moderate infestation of 16 seedlings m^{-2} in the subsequent wheat crop. Simulations were conducted for a period of 25 years, which was long enough to achieve population stabilization.

Different control scenarios were simulated representing different clodinafop doses in the wheat year: the standard farmer practice (full dose 100% of the label rate of Topik 24®, 250 mL ha^{-1}), resulting in an assumed efficiency of 98% weed control (according to our simulations, correspond to the minimum value of efficiency to decreasing seed bank); 75% of the recommended dose (80% control efficiency), 50% of the recommended dose (70% control efficiency), and no

Table 1. Model parameters values for the wheat and sunflower submodels

Parameter	Value
Wheat sub model	
Emergence (g)	0.16
Seedling survivorship (s)	0.19
Seedbank mortality (m)	0.50
Fecundity (f) (seeds plant^{-1})	1,454
Seed lost (p)	0.90
Sunflower sub model	
Rate of seeds transferred to the deep seed bank after mouldboard plough (l_1)	0.03
Survival of seeds after mouldboard plough (d_1)	0.75
Rate of seeds transferred to the deep seed bank after rotary harrow passes (l_2)	0.49
Rate of seeds transferred to the surface seed bank after harrow passes (l_3)	0.20
Survival of seeds after rotary harrow (d_2)	0.50
Herbicide control (c), for:	
100% recommended rate	0.98
75% recommended rate	0.80
50% recommended rate	0.70

herbicide application (0% control efficiency). Assumed efficiencies for both reduced-dose scenarios (80 % and 70%) were obtained from Gonzalez-Diaz *et al*. (2009); after a literature revision, it seems there are no references on this point except our unpublished data. However, any possible variation in the population as consequence of the variation in the control percentage is explained by the sensitivity analysis of seedling survivorship.

Sensitivity analysis

A sensitivity analysis was carried out to assess the sensitivity of the model to variations in demographic parameters. We used the sensitivity coefficient (ε) suggested by Pannell (1997). This sensitivity index is given by:

$$\varepsilon = \frac{\left(\frac{f(p+\Delta p)}{f(p)}\right)}{\frac{\Delta p}{p}} \quad [7]$$

where, p is the standard value of the parameter being analyzed, Δp is a deviation from this value, and f represents the model output (seed bank density). A large value of ε indicates that a small variation in the parameter will result in a large modification in the model output. Sensitivities after 25 years were determined by modifying individual parameter values by ± 40%. This variation range was chosen because it roughly corresponds to the largest variation observed in field data previously used for parameter estimation in demographic studies with *Avena sterilis* (Gonzalez-Diaz *et al*., 2009).

Results and discussion

With no herbicide application, the seed bank population of the weed increases steadily up to an equilibrium density of 54,859 seeds m^{-2}, corresponding to 575 plants m^{-2} (Fig. 2). These seed and plant densities can be considered the carrying capacity of short-spiked canary grass populations in the wheat-sunflower rotation system under the specified set of conditions.

Simulation results indicate that herbicide applications at full rate would result in a long-term population size of 26 seeds m^{-2} (4 plants m^{-2}) (Fig. 2), representing only 1% of the carrying capacity of the system. Because of their lower control efficacy compared to the full dose, the strategies based on reduced herbicide doses are predicted to not decrease seed bank densities in the long term (Fig. 2).

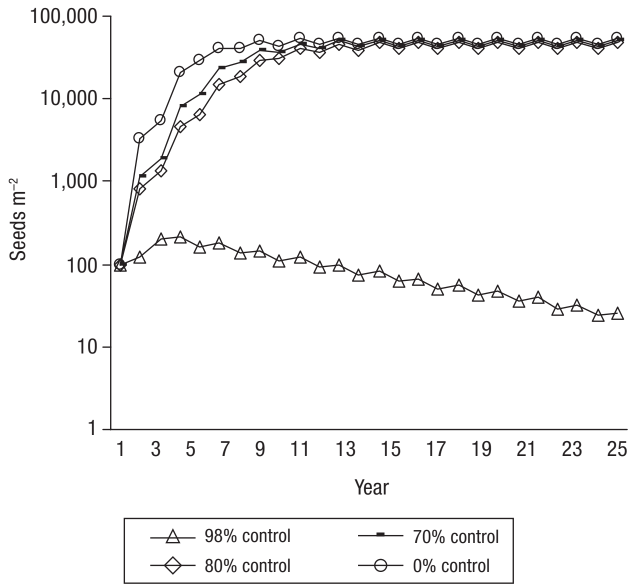

Figure 2. Simulated seedbank dynamics of *Phalaris brachystachys* in wheat-sunflower rotation under different herbicide doses: 100% (98% of control), 75% (80% of control), 50% (70% of control) and 0% (0% of control) of the standard recommended rate.

Sensitivity analyses showed that seedling survival and fecundity were the most sensitive demographic parameters under the full dose strategy, and fecundity and seedbank mortality were the most sensitive parameters under both reduced-dose strategies (Table 2). It should be noted that reduced dose strategies tend to be less sensitive than the full dose strategy (Table 2).

In absence of weed control measures, the seed bank of *P. brachystachys* in the wheat-sunflower cropping system in southern Spain is predicted to reach large densities in the long term. According to Cudney & Hill (1979), such infestation levels are expected to result in yield losses greater than 60%. The predicted equilibrium density in the studied wheat-sunflower rotation is 38% larger than previously reported for a wheat monoculture (Gonzalez-Diaz *et al*., 2009). This indicates that the sub-optimal conditions imposed on the weed by the sunflower crop do not last enough to control the build-up of *P. brachystachys* populations in this crop rotation system. Some authors claim that in general, crop rotation reduces weed populations in comparison to monoculture systems (Liebman & Dyck, 1993); but

Table 2. Sensitivity analysis for different demographic parameters of *Phalaris brachystachys* seed bank in a wheat-sunflower rotation system under different herbicide-based control strategies

Parameter	% Change in parameter	Sensitivity coefficients			
		Full herbicide dose (98% control)	75% dose (80% control)	50% dose (70% control)	Without herbicide application (0% control)
Emergence	+ 40	29.23	2.52	2.49	2.44
	– 40	0.00	0.00	0.00	1.59
Seedling survivorship	+ 40	49.81	2.61	2.57	2.52
	– 40	0.10	2.22	2.32	2.45
Seedbank mortality	+ 40	12.60	3.05	3.02	2.98
	– 40	0.38	2.10	2.12	2.14
Fecundity	+ 40	44.42	3.65	3.20	3.52
	– 40	0.10	1.35	1.40	1.47
Seed loss	+ 40	6.06	2.82	2.80	2.78
	– 40	0.10	1.35	1.40	1.47

the rotation must be accompanied by other management strategies to effectively reduce populations of *P. brachystachys*. In our case, probably due to the high fecundity of *P. brachystachys* in the wheat crop, the effect of the crop rotation is not enough to drive the weed population to extinction, at least in 25 years.

Herbicide applications at the standard rate (98% control) resulted in an effective long-term control, substantially reducing the population size in the non-control scenario (Fig. 2). The increasing rate in the case of simulated weed control options based on reduced herbicide was slowing down, but the seed bank still was increasing (even if at a smaller rate) until it got to a steady state (Fig. 2). Low effectiveness of reduced-dose herbicide applications allows survival of some plants every wheat year that are able to build up the *P. brachystachys* soil seed population, eventually reaching the population density in the non-control scenario. Moreover, the use of low herbicide doses may lead to the development of polygenic herbicide resistant populations (Gressel, 2002).

Our results do not support the re-evaluation of conventional decision-making methods by using only reduced dose strategies in combination with wheat-sunflower rotation to control *P. brachystachys*, as suggested by some authors (Gaitan *et al*., 2007). Using management practices that increases crop competitiveness may reduce the negative effects associated with the use of low herbicide rates. Different studies have shown that control of sterile oat (*Avena sterilis*) and paradoxa grass (*Phalaris paradoxa*) populations can be improved by using competitive crop cultivars and high seeding rates (Walker *et al*., 2002; Fernandez-Quintanilla *et al*., 2006). Integrating these practices with the use of low herbicide rates may provide an agronomically viable and environmentally friendly solution for short-spiked canary grass control under semi-arid conditions.

Sensitivity analysis indicated that there was a marked difference in terms of sensitivity values between the different control options (full dose and reduced doses of herbicides), showing that reduced doses tend to be less affected by parameter variations than the full dose strategy. Differences in sensitivity between different control strategies have been pointed out for sterile oat (*Avena sterilis*) growing in winter wheat (Gonzalez-Andujar & Fernandez-Quintanilla, 1993).

Although the resistance is not the main objective of the paper, it might affect the value of some demographic parameters. But any possible variation in the parameter's value and their effect on the population are provided by the sensitivity analysis done.

The current model offers some practical guidance regarding the possibilities and limitations of different strategic approaches for the control of this weed. The two most sensitive demographic parameters under the full dose strategy were fecundity and seedling survival, whereas fecundity and seedbank mortality were the most sensitive parameters under reduced dose strategies. Consequently, development of specific management strategies to target these demographic parameters would be valuable for improving control of *P. brachystachys* in the wheat-sunflower cropping system. Additionally, the modelling approach used in this study could be extended to other annual plants with comparable life-history characteristics under a rotation system.

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References

Afentouli CG, Eleftherohorinos IG, 1999. Competition between wheat and canarygrass biotypes and their response to herbicides. Weed Sci 47: 55-61.

Bullock J M, Pywell RF, Coulson-Phillips SJ, 2008. Managing plant population spread: prediction and analysis using a simple model. Ecol Appl 18: 945-953.

Cudney DW, Hill JE, 1979. The response of wheat grown with three population levels of canarygrass to various herbicide treatments. Proc West Soc Weed Sci, Boise, ID, USA, March 20-22, pp: 55-56.

Fernandez-Quintanilla C, Leguizamon E, Navarrete L, Sanchez El Arco M, Torner C, De Lucas C, 2006. Integrating herbicide rate, barley variety and seeding rate for the control of sterile oat (*Avena sterilis* spp. *luvodicina*) in central Spain. Eur J Agron 25: 223-233.

Gaitan A, Solis I, Gonzalez-Andujar JL, Perea F, Urbano JM, 2007. Utilización de dosis reducidas de antigramíneas para el control de *Avena sterilis* ssp. *sterilis* y *Phalaris* spp en Andalucía. In: La Malherbología en los nuevos sistemas de producción agraria (Mansilla J, Artigao A, Monreal JA, eds). Universidad de Castilla-La Mancha, Spain, pp: 229-234. [In Spanish].

Gonzalez-Andujar JL, Fernandez-Quintanilla C, 1993. Strategies for the control of *Avena sterilis* in winter wheat production systems in central Spain. Crop Prot 12: 617-623.

Gonzalez-Andujar JL, Saavedra M, 2003. Spatial distribution of annual grass weed populations in winter cereals. Crop Prot 22: 629-633.

Gonzalez-Andujar JL, Jimenez-Hidalgo M, Garcia Torres L, Saavedra M, 2005. Demography and population dynamic of the arable weed *Phalaris brachystachys* (short-spiked canary grass) in winter wheat. Crop Prot 24: 581-584.

Gonzalez-Díaz L, Bastida F, Gonzalez-Andujar JL, 2009. Modelling of the population dynamics of *Phalaris brachystachys* Link under various herbicide control scenarios in a Mediterranean climate. Span J Agric Res 7: 155-159.

Gressel J, 2002. Evolution of resistance to herbicides. In: Molecular biology of weed control. Taylor & Francis, London, 520 pp.

Holst N, Rasmussen IA, Bastiaans L, 2007. Field weed population dynamics: a review of model approaches and applications. Weed Res 47: 1-14.

Jimenez-Hidalgo MJ, 1993. Incidencia y evolución de los alpistes (*Phalaris sp.*) en el trigo (*Triticum sp.*). Doctoral thesis, Universidad de Córdoba, Spain. [In Spanish].

Jimenez-Hidalgo MJ, Saavedra M, Garcia-Torres L, 1997. *Phalaris brachystachys* in cereal crops. In: Biology of weeds in Spain (Sans X, Fernandez-Quintanilla C, eds). Phytoma-España, Valencia, Spain, pp: 77-89. [In Spanish].

Liebman M, Dyck E, 1993. Crop rotation and intercropping strategies for weed management. Ecol Appl 3: 92-12.

Pannell D, 1997. Sensitivity analysis of normative economic models: theoretical framework and practical strategies. Agric Econ 16: 139-152.

Saavedra M, Cuevas J, Mesa-Garcia J, Garcia-Torres L, 1989. Grassy weeds in winter cereals in southern Spain. Crop Prot 8: 181-187.

Walker S, Medd R, Robinson G, Cullis B, 2002. Improved management of *Avena ludoviciana* and *Phalaris paradoxa* with more densely sown wheat and less herbicide. Weed Res 42: 257-270.

Zhang J, Weaver S, Hamill A, 2000. Risks and reliability of using herbicides at below-labeled rates. Weed Technol 14: 106-115.